BP Solar International, Inc. (formerly Solarex, Inc.)

Development of Rapid Thermal Processing to Produce Low-Cost Solar Cells

Solar cells collect energy from the sun and convert the energy into electricity. In 1994, the process to manufacture solar cells was lengthy and costly; they were processed in electric hot-air furnaces that took two hours to preheat and consumed much energy. Solar cells are made from silicon wafers, which are costly. The lengthy processing time made the overall cost of solar energy two to three times higher than standard grid-connected electricity. In order to make solar energy more competitive with conventional electricity from gas-fired power plants, Solarex, Inc. proposed to develop a new method to process solar cells called Rapid Thermal Processing (RTP). RTP would use a high-speed hybrid infrared-ultraviolet-light heat source, which would reduce the temperature needed to process the cells. Preliminary laboratory research at Clemson University and the Georgia Institute of Technology (Georgia Tech) indicated that RTP could replace time-consuming, high-temperature, hot-air furnace-based manufacturing steps, resulting in an increase in the rate of production and a reduction in energy consumption. RTP technology was high risk: the type of multiple-stage furnace used to heat wafers had never been built before. Moreover, to make the new process cost effective, the furnace would need to process a high volume, whereas only single wafers had been processed with RTP in the laboratory. Solarex applied for Advanced Technology Program (ATP) funding in 1994 in order to support comprehensive modeling and design to develop a streamlined RTP manufacturing process.

ATP awarded cost-shared funding to Solarex for three years, beginning in 1995. Solarex teamed with Clemson and Georgia Tech to develop a prototype fast-heating hybrid infrared-ultraviolet furnace, which became stable and hot within 15 minutes. Solar cells were processed in 1 to 2 minutes, a dramatic reduction from the 20 minutes required in the hot-air furnace. Unfortunately, exhaust gases produced during fabrication damaged the lamps in the furnace, which became clouded and lost effectiveness. Researchers were unable to mitigate the exhaust problem, but did gain knowledge about automating and quickly processing cells. In 1999, BP Solar International, Inc. acquired Solarex and continues to build on the research and knowledge gained in this ATP-funded project. BP Solar is working to meet the growing demand for higher efficiency and throughput of solar cells in order to reduce dependence on conventional power sources.

COMPOSITE PERFORMANCE SCORE

(based on a four star rating)

* *

Research and data for Status Report 94-01-0330 were collected during July – August 2004.

Solar Cells Were Expensive to Produce

Solar cells convert sunlight directly into electricity. On a sunny day, the sun shines approximately 1,000 watts of energy per square meter of the earth's surface. Solar cells, most often made from wafers of crystalline silicon, convert this sunlight energy into electricity. Solar cells produce no emissions, have no moving parts, cost little to operate and maintain, and last more than 20 years. They provide reliable, economical power, especially where grid power is not available. In the early 1950s, the devices were used primarily to make solar-powered radios, toy ships, and other playthings. In 1958, solar cells gained recognition when the U.S. Navy launched the first solar-powered satellite, Vanguard I. More practical solar applications emerged in the 1970s: safety lights on off-shore oil and gas rigs and along railroad tracks; lighthouses, buoys, and other navigational safety equipment; and as a replacement for conventional grid-connected power in remote locations that were often far from conventional power stations and power lines. Solar energy is especially valuable in remote parts of the United States or in developing nations, where it offers a direct and safe alternative to kerosene lamps and diesel generators.

Solar cells are manufactured from a thin slice (about 200 micrometers thick), or wafer, of high-quality silicon layered and laminated with electrically interconnected sections under glass and processed with heat. The silicon wafer becomes a one-way energy conductor when it is treated with phosphorous. Electrical contacts are deposited by screen-printing and are fired afterwards. At the end of the process, an anti-reflection coating is deposited on the front side of the cell.

The time and energy needed to process the silicon wafers adds significantly to the cost of producing solar cells. Silicon wafers, or chips, were traditionally processed in high-temperature electric furnaces, which took up to two hours to preheat and stabilize, because the whole furnace had to reach equilibrium. Heating the wafers in the furnace then took 20 minutes. A conventional, 20-foot furnace, operating 24 hours a day, used approximately 30 kilowatts (kW) of energy every hour, 720 kW per day, and 262,800 kW per year.

Large, high-purity single crystals of silicon produce high-performance cells capable of converting around 25 percent of available sunlight into electricity, and efficiencies up to 30 percent had been demonstrated. But these high-end cells, which had proven to be durable in space applications, were very costly to produce because of the energy-intensive and slow silicon single-crystal growth and manufacturing processes. Moreover, while higher efficiencies had been achieved, most panels were only 10 to 12 percent efficient.

The per-watt cost of solar electricity in 1994 was two to three times that of conventional power; therefore, the manufacturing cost had to be reduced to make solar power more competitive with other energy sources on a large scale. Concern about the environment and the depletion of petroleum reserves was focusing attention on solar and other alternative energy resources.

Solarex Proposes a New Method to Process Solar Cells

Solarex, Inc. collaborated with Clemson University and the Georgia Institute of Technology (Georgia Tech) and submitted a proposal to ATP in 1994. They would develop a process for solar cell manufacturing that was more energy-efficient and faster. They intended to replace the high-temperature hot-air furnaces used for silicon chip processing with a technique called Rapid Thermal Processing (RTP). RTP uses light to heat the wafers directly rather than heating the ambient environment in the furnace. RTP relied on infrared lamps that provided both heat and ultraviolet (UV) light to process the chips.

ATP awarded Solarex cost-shared funding for three years, beginning in 1995. If successful, RTP would reduce the footprint of the manufacturing facility, streamline and automate the manufacturing process for solar cells, and reduce energy consumption. Researchers projected that RTP could reduce manufacturing costs $1.50 to $2.00 per peak watt, less than half the 1994 cost of $4.50 per peak watt. A cost of less than $3.00 to $4.00 was considered competitive. Reduced production costs could lead to lower prices, opening new markets for solar energy.

The time and energy needed to process the silicon wafers adds significantly to the cost of producing solar cells.

Because RTP had been demonstrated only in a laboratory setting, researchers faced the following significant technical risks:

- They needed to develop a continuous throughput RTP furnace that had multiple lamps and was automated with conveyor belts, a furnace that had never been built before.

- The team needed to scale up from an experimental wafer-processing laboratory environment that processed 60 100-cm^2 silicon wafers per hour to much larger sizes and quantities (1,300-cm^2 wafers at 2,000 per hour). This would require automating the process, using larger equipment, and rearranging the footprint of the factory floor.

- Researchers needed to achieve energy conversion efficiencies equal to that of solar cells from conventional furnaces, which were then at 12.5 percent efficiency.

Solarex Intended to Improve Solar Cell Processing

The heart of a solar cell is a silicon wafer, which is a light-sensitive, semiconducting material. Photons (light) shining on the semiconductor excite electrons. The process generates electron-hole pairs (pairs of negative and positive charge carriers). Small amounts of substances like boron or arsenic, called dopants, are added to the silicon semiconductor to alter its electrical characteristics. The doped semiconductor then contains a negatively charged (n-type) layer and a positively charged (p-type) layer. Excited electrons migrate toward the positive side of the junction, leading to a flow of electric current.

Rapid Thermal Processing (RTP) would reduce the footprint of the manufacturing facility, streamline and automate the manufacturing process for solar cells, and reduce energy consumption.

RTP uses infrared heat to cause the n-type dopant atoms to react with the p-type silicon, making an n-p junction, or diode. A diode is the electronic version of a one-way valve: by restricting the direction of movement of charge carriers, it allows an electric current to flow in one direction, but blocks it in the opposite direction. Solarex researchers believed they could drive the chemical reaction faster with light energy focused directly on the silicon wafer and reduce energy consumption by using a combination of infrared and UV light. Lowering the total energy consumption and increasing the processing speed would dramatically reduce energy cost per wafer. In addition, researchers anticipated reduced electronic defects, which would lead to higher light-to-energy conversions within the manufactured solar cells.

Several subcontractors supported the ATP-funded project. Clemson University had RTP equipment that was capable of processing small, single wafers. With modification, Solarex believed this equipment could be used to process large-area polycrystalline wafers in large quantities. Clemson agreed to transfer its technology to Solarex. Georgia Tech supported the project with its expertise in solar cell materials, devices, processes, modeling, and characterization. Automation and Robotics Research Institute (ARRI) developed the wafer-transport system. Vortek Industries and Radiant Technology Corp. (RTC) provided prototype lamps and furnaces.

The project goals were to enhance solar cell manufacturing technology by reducing process cost, reducing energy consumption in the fabrication process, improving conversion efficiency, and increasing production capacity. An additional goal was to reduce the number of years required to recoup investments from solar power production. At the time of the project, recoupment time was estimated at 1.7 to 6.4 years. If successful, this project would reduce energy payback time by 50 to 67 percent.

Solarex Builds a Prototype RTP Furnace

Solarex built a prototype RTP furnace based on argon arc lamps (AAL), which reduced cell processing time. AALs have more high-energy visible photons and UV photons (electromagnetic particles of light), which provide quantum (electromagnetic energy) enhancement during processing. Vortek Industries designed the AALs. RTC, one of the few solar cell furnace manufacturers, produced the RTP-based furnaces, and ARRI designed the wafer conveyor-belt transport system.

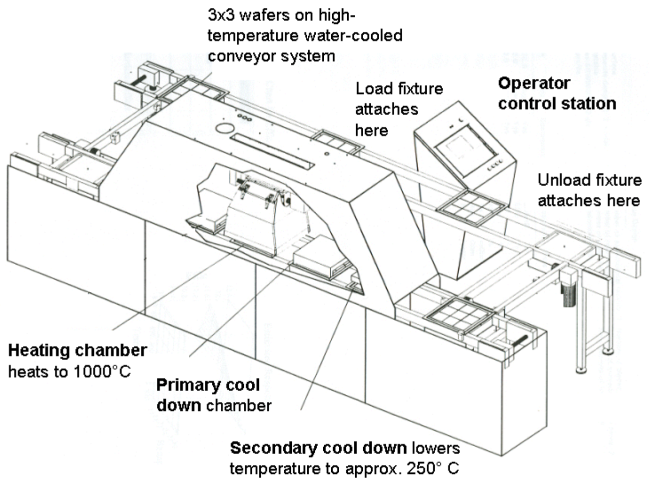
The AAL provided infrared light as well as UV light. Infrared waves excite molecular vibrations within a substance, thus generating heat within the silicon wafer and not in the ambient environment. As a result, infrared light's radiation allows reactions to take place faster. UV light is on the upper end of the color spectrum, so it has high frequencies and energy that can reduce defect densities. Although they had problems with the lamps, the Solarex team did couple infrared energy with UV light and develop a hybrid infrared-UV furnace (see illustration below) with the following results:

- Heated and stabilized the chamber in 15 minutes. Silicon wafers moved through the furnace on a conveyor belt rapidly, in 1 to 2 minutes. This saved significant energy compared with a traditional hot-air furnace, which took up to 2 hours to heat and stabilize. Furthermore, the silicon wafers then took 20 minutes to move through the hot-air furnace. Silicon wafers require heat treatment to make the necessary doped-device layers and light-absorbing layers and to apply contacts.

- Increased the size of the chamber to 1,300 cm^2 and achieved a throughput of 1,000 wafers per hour (increased from 60 wafers per hour, but short of the target 2,000 wafers per hour).

- Received one patent for the ATP-funded technology.

- Demonstrated 11.8-percent efficiency in the processed solar cells.



Cut-away diagram of the RTP furnace that Vortek assembled for Solarex. Nine solar cells (for a combined 1,300 cm^2) were automatically loaded, were moved via high-speed conveyor belts through the heating and cooling chambers, and were unloaded. Infrared and UV light provided additional energy, which allowed silicon-processing reactions to take place faster at a lower temperature and with less energy. The high speed increased throughput and reduced energy consumption per wafer. The operator monitored the processing parameters to assure quality.

Technical Difficulties Bar Commercialization

Following some initial success, Solarex researchers had trouble with the lamps in the furnace after they had been used several times. The manufacturing process included putting phosphoric acid onto the wafer before sending the wafer through the furnace. The phosphoric acid coating burned off, causing exhaust gases to arise and cloud and reduce lamp radiation. Researchers were unable to adequately remove these exhaust gases, which rendered the lamps and furnace unusable.

The ATP-funded project initiated interest in using RTP for solar cell processing and contributed to the advancement of knowledge in this field. RTC continues to use two types of infrared heating (without UV lamps) in its solar processing furnaces, near infrared and medium-range infrared lamps. Near-infrared furnaces can reach temperatures up to 1,000°C, while medium-range infrared furnaces are able to reach temperatures up to 1,300°C. These furnaces use up to 75 percent less energy than traditional hot-air furnaces.

In 1999, Solarex was acquired by BP Corporation North America, Inc. Solarex changed its name to BP Solar International, Inc. and is a division of BP Corporation.

Researchers Continue Development of RTP

As of 2004, efforts to improve solar cell efficiency were continuing. BP Solar received funding from the U.S. Department of Energy to work with Georgia Tech to study RTP methods for firing the electrical contacts on solar cells. Because Solarex's proposed use of UV light was not viable, Georgia Tech researchers continue to develop the RTP technology relying on infrared radiation. They are sharing their project knowledge extensively through presentations and articles. Laboratory experiments firing at high speed have helped reduce defects, improving efficiency to almost 16 percent. RTP is a promising technique that is still being explored by the solar industry. As a result of this project, interest has been kindled. The industry is beginning to recognize RTP technology's potential to reduce energy consumption in manufacturing and improve efficiency of manufactured cells through reduced electronic defects.

Demand Continues to Increase

BP Solar invests in RTP technology because demand for solar energy is rising dramatically. Global demand for solar energy grew at 37 percent per year between 2001 and 2003 and is expected to continue this pace for some years. Global installations of solar cells reached 574 megawatts (MW) in 2003, with sales at $1 billion. This was an increase from 26 MW in 1994 and sales of $118 million. BP Solar's 2003 sales of solar cells were $300 million, which represented a 16-percent market share. Global sales of $1.4 billion are anticipated by 2008. In October 2004, BP Solar announced that they intend to double their manufacturing capacity by the end of 2005.

The industry is beginning to recognize Rapid Thermal Processing (RTP) technology's potential to reduce energy consumption in manufacturing and improve efficiency of manufactured cells through reduced electronic defects.

BP Solar seeks to develop improved solar cells, because solar energy is a desirable, nonpolluting, renewable energy source. Governments throughout the world, particularly in Japan and Germany, are supporting solar energy as a means to address climate change, energy security, consumer demand, and economic development. In the United States, California has offered income tax credits for the purchase and installation of solar systems since 2001 and will continue to offer the credits through 2005. California also began offering rebates for the purchase of grid-connected solar systems in 2005. Governor Arnold Schwarzenegger is leading a state campaign to generate 3 gigawatts (GWs; or 3 million kilowatts) of solar electricity by 2017 as part of a plan to derive 33 percent of the state's power from renewable sources by 2020. Three GWs represents 5 percent of 2005 statewide peak demand, or the equivalent of five power plants. One GW is enough to light 100 million homes. Energy experts estimate California will need 1 new GW per year to keep up with a growing economy and prevent the kind of power shortages that plagued the state in 2000 and 2001. New Jersey, New York, and Pennsylvania are also developing solar initiatives. A group of 18 western states is working to develop 30 GWs of clean energy by 2015. If solar power installations can replace fossil-energy-fired plants, the utility industry can reduce harmful air pollutants.

Conclusion

Although Solarex (later BP Solar International, Inc.) did not commercialize Rapid Thermal Processing (RTP) of solar cells, the company gained important knowledge and made valuable advances. Replacing time-consuming, high-temperature, hot-air furnace-based manufacturing steps with RTP could increase throughput (rate of production) and reduce energy consumption, key elements in the cost of producing solar cells. Researchers achieved many of their technical goals and developed a prototype automated, high-speed RTP furnace. ATP support allowed the researchers to develop one patent and improve the throughput, size, and quality of its solar cells. However, burning phosphoric acid clouded the lamps in the furnace, a problem that researchers could not overcome and that ultimately prevented commercialization of the RTP process. Ongoing research at BP Solar and the Georgia Institute of Technology (Georgia Tech), funded by the U.S. Department of Energy and others, continues to enhance solar cell efficiency as a means to reduce pollution and dependence on nonrenewable resources. Researchers have improved solar cell energy conversion efficiency from 12 percent in 1998 to almost 16 percent in 2004 using RTP. Researchers from Georgia Tech and BP Solar ultimately hope to commercialize RTP for higher efficiency solar cells in response to the global market demand. Demand has been increasing about 20 percent per year since the 1980s, with an increase to 37 percent per year from 2001 to 2003.

PROJECT HIGHLIGHTS
BP Solar International, Inc. (formerly Solarex, Inc.)

Project Title: Development of Rapid Thermal Processing to Produce Low-Cost Solar Cells

Project: To develop low-cost solar cells for solar energy production by replacing time-consuming, high-temperature, furnace-based manufacturing steps with rapid thermal processing (RTP).

Duration: 2/23/1995–2/22/1998
ATP Number: 94-01-0330

Funding (in thousands):

ATP Final Cost	$1,752	59%
Participant Final Cost	1,237	41%
Total	$2,989	

Accomplishments: With ATP funding, researchers focused their efforts on processing solar cells using RTP. Although they were not able to develop a commercialized solar cell process due to a problem with exhaust gases, they had several successes:

- Reduced furnace preheating time from 2 hours to 15 minutes
- Reduced solar cell processing time from 20 minutes to 1 to 2 minutes
- Increased heating chamber size from 100 cm^2 to 1,300 cm^2
- Increased throughput from 60 silicon wafers per hour to 1,000 wafers per hour
- Improved solar cell energy efficiency from 14.5 percent to almost 16 percent as of 2004 in development that continued after the ATP-funded project ended; efficiency was at 12 percent in 1998 at project conclusion

In addition, technology from this project led to one award:

- Best doctoral dissertation, Georgia Institute of Technology, "Fundamental Understanding and Integration of Rapid Thermal Processing, PECVD, and Screen Printing for Cost Effective High Efficiency Silicon Photovoltaic Devices," by Parag M. Doshi, 1998.

Researchers were awarded one patent from this ATP-funded technology:

- “Process for forming layers on substrates” (No. 6,569,249: filed April 18, 2000; granted May 27, 2003)

Commercialization Status: BP Solar International, Inc. (a division of BP Corporation North America Inc.) has no plans to commercialize RTP for solar cells in the near future. Researchers gained knowledge of solar cell processing and continue to develop potential applications for long-term future applications.

Outlook: The long-term outlook for RTP of solar cells is good, if the energy conversion efficiency rates achieved in the laboratory can be transferred to commercial production. Researchers are publishing many articles, and they expect manufacturers to adopt their methodologies in the future. Demand for solar energy grew at 37 percent annually from 2001 to 2003. Manufacturers desire improvements in efficiency and throughput in order to keep up with demand.

Composite Performance Score: * *

Number of Employees: 399 employees at project start (Solarex), 380 as of September 2004 (BP Solar)

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Subcontractors:

- Automation and Robotics Research Institute
  Arlington, TX
- Clemson University
  Clemson, SC
- Georgia Institute of Technology
  Atlanta, GA
- Radiant Technology Corp. (RTC)
  Fullerton, CA
- Vortek Industries
  Vancouver, BC, Canada

PROJECT HIGHLIGHTS
BP Solar International, Inc. (formerly Solarex, Inc.)

Publications: Researchers at BP Solar, Clemson University, and Georgia Tech shared their knowledge through the following 27 publications, beginning in 1996 and continuing through 2004.

- Doshi, P., J. Mejia, K. Tate, and A. Rohatgi. “Integration of Screen-Printing and Rapid Thermal Processing Technologies for Silicon Solar Cell Fabrication.” *IEEE Electron Device Letters*, Vol. 17, No. 8, pp. 404-409, August 1996.

- Cai, L., D. Yang, M.A. El-Sayed, and A. Rohatgi. “Effects of Rapid Thermal Anneal on Refractive Index and Hydrogen Content of Plasma-Enhanced Chemical Vapor Deposited Silicon Nitride Films.” *Applied Physics Letters*, Vol. 80, No. 9, pp. 5384-5388, November 1996.

- Singh, R., K.C. Cherukuri, L. Vedula, A. Rohatgi, J. Mejia, and S. Narayan. "Enhanced Diffusion and Improved Device Performance Using Dual Spectral Source Rapid Thermal Processing." *J. Electronics Materials*, Vol. 26, No. 12, pp. 1422-1427, 1997.

- Vedagarbha, V., L. Vedula, R. Sharangpani, R. Singh, A. Rohatgi, and S. Narayan. "Defect Reduction and Improved Device Performance Using Dual Spectral Source Rapid Isothermal Diffusion in Silicon." *Mat. Res. Soc. Proc.*, Vol. 469, pp. 437-442, 1997.

- Singh, R., and R. Sharangpani. “Rapid Photothermal Processing.” *Solid State Technology*, Vol. 40, No. 10, pp. 193-198, May 1997.

- Doshi, P., J. Mejia, K. Tate and A. Rohatgi. “Modeling and Characterization of High-Efficiency Silicon Solar Cells Fabricated by Rapid Thermal Processing, Screen Printing, and Plasma Enhanced Chemical Vapor Deposition.” *IEEE Transactions of Electron Devices*, Vol. 44, No. 9, pp. 1417-1424, September 1997.

- Ratakonda, D., R. Singh, L. Vedula, A. Rohatgi, J. Mejia, and S. Narayanan. “Rapid Thermal Processing of Screen Printed Ohmic Contacts.” *Journal of Electrochemical Society*, Vol. 144, No. 9, pp. 3237-3242, September 1997.

- Sharangpani, R., and R. Singh. "Role of Rapid Photothermal Processing in Environmentally Conscious Semiconductor Manufacturing." *J. of Materials Research*, Vol. 13, pp. 61-67, 1998.

- Narasimha, S. and A. Rohatgi. “Effective Passivation of the Low Resistivity Silicon Surface by a Rapid Thermal Oxide/Plasma Silicon Nitride Stack.” *Applied Physics Letters*, Vol. 72, pp. 1872-1874, April 1998.

- Singh, R., V. Vedagarbha, and S. Narayan. "Using Different Lamp Configurations in Rapid Thermal Processing." *J. Vac. Sci and Tech*, Vol. 16, pp. 613-618, May 1998.

- Doshi, P. and A. Rohatgi. “18-Percent Efficient Silicon Photovoltaic Devices by Rapid Thermal Diffusion and Oxidation.” *IEEE Transactions on Electron Devices*, Vol. 45, No. 8, pp. 1710-1716, August 1998.

- Singh, R., V. Parihar, S. Venkataraman, K.F. Poole, R.P.S. Thakur, and A. Rohatgi. “Changing from Rapid Thermal Processing to Rapid Photothermal Processing: What Does It Buy for a Particular Technology?” *Materials Science in Semiconductor Processing*, pp. 219-230, 1999.

- Singh, R., A. Rohatgi, and K. F. Poole. "Rapid Thermal Processing as a Photovoltaic Manufacturing Technology for the 21st Century." *Electrochemical Society Proceedings*, Vol. # PV 99-11, pp. 33-48, 1999.

- Krygowski, T., A. Rohatgi and T. Selzer. “A Novel Processing Technology for High-Efficiency Silicon Solar Cells.” *Journal of the Electrochemical Society*, Vol. 146, No. 3, March 1999.

- Rohatgi, A., S. Narasimha, P. Doshi, A. Ebong, and J. Moschner. “Rapid Thermal Processing and Screen-Printing for Low Cost Silicon Solar Cells.” *American Institute of Physics*, NCPV Photovoltaics Program Review, edited by M. Al-Jassim, J.P. Thornton, and J.M. Gee, pp. 354-360, March 1999.

- Rohatgi, A., S. Narasimha, A. Ebong and P. Doshi. “Understanding and Implementation of Rapid Thermal Technologies for Low-Cost High-Efficiency Silicon Solar Cells.” *IEEE Transaction on Electron Devices*, Vol. 46, No. 10, pp. 1970-1977, October 1999.

PROJECT HIGHLIGHTS
BP Solar International, Inc. (formerly Solarex, Inc.)

- Venkataraman, S., R. Singh, V. Parihar, K. F. Poole, A. Rohatgi, V. Yelundur, and A. Ebong. “A Study of the Effect of Ultraviolet (UV) and Vacuum Ultra Violet (VUV) Photons on the Minority Carrier Lifetime of Single Crystal Silicon Processed by Rapid Thermal and Rapid Photothermal Processing.” *Journal of Electronic Materials*, Vol. 28, No. 12, pp. 1394-1398, December 1999.

- Rohatgi, A., P. Doshi, J. Moschner, T. Lauinger, A. Aberle, and D. S. Ruby. “Comprehensive Study of Rapid, Low-Cost Silicon Surface Passivation Technologies.” *IEEE Transaction on Electron Devices*, Vol. 47, No. 5, pp. 987-993, May 2000.

- Rohatgi, A., A. Ebong, V. Yelundur, and A. Ristow. “Rapid Thermal Processing of Next Generation Silicon Solar Cells.” *Progress in Photovoltaics Research and Applications*, Vol. 8, pp. 515-527, July 2000.

- Jeong, J. W., A. Rohatgi, V. Yelundur, A. Ebong, M.D. Rosenblum and J.P. Kalejs. “Enhanced Silicon Solar Cell Performance by Rapid Thermal Firing of Screen Printed Metals.” *IEEE Electron Devices Society*, Vol. 48, No. 12, pp. 2836-2841, May 2001.

- Yelundur, V., A. Rohatgi, J.W. Jeong, and J. Hanoka. “Improved String Ribbon Silicon Solar Cell Performance by Rapid Thermal Firing of Screen-Printed Contacts.” *IEEE Transaction on Electron Devices*, Vol. 49, No. 8, pp 1405-1410, February 2002.

- Rohatgi, A. and J.W. Jeong. “High Efficiency Screen-Printed Silicon Ribbon Solar Cells by Effective Defect Passivation and Rapid Thermal Processing.” *Applied Physics Letters*, Vol. 82, No. 2, pp 224-226, July 2002.

- Ebong, A., Y.H. Cho, M. Hilali, A. Rohatgi and D. Ruby. “Rapid Thermal Technologies for High Efficiency Silicon Solar Cells.” *Solar Energy Materials & Solar Cells*, Vol. 74. pp. 51-55, August 2002.

- Rohatgi, A., D.S. Kim, K. Nakayashiki, V. Yelundur, and B. Rounsaville. “High-Efficiency Solar Cells on Edge-Defined Film-Fed Grown (18.2%) and String Ribbon (17.8%) Silicon by Rapid Thermal Processing.” *Applied Physics Letters*, Vol. 84, No.1, pp. 145-147, January 2004.

- Rohatgi, A., M. Hilali, and K. Nakayashiki. “High-Efficiency Screen-Printed Solar Cell on Edge-Defined Film-Fed Grown Ribbon Silicon Through Optimized Rapid Belt Co-Firing of Contacts and High-Sheet-Resistance Emitter.” *Applied Physics Letters*, Vol. 84, No. 3409, pp. 152-154, February 2004.

- Nakayashiki, K., V. Meemongkolkiat, and A. Rohatgi. “High Efficiency Screen-Printed EFG Si Cells Through Rapid Thermal Processing-Induced Bulk Lifetime Enhancement.” *Progress in Photovoltaics*, May 2004.

Presentations: Researchers also gave numerous presentations from 1995 to 2004.

- Rohatgi, A., P. Doshi, M. Ropp, L. Cai, A. Doolittle, S. Narasimha, T. Krygowski, J. Rand, D. Ruby, and D. L. Meir. “Improved Understanding and Optimization of RTP and PECVD Processes for High Efficiency Silicon Solar Cells.” European Photovoltaic Solar Energy Conference and Exhibition, Nice, France, October 1995.

- Singh, R., A. Rohatgi, and D. Ratokonda. “Role of Rapid Isothermal Processing in the Manufacturing of Bulk and Thin Film Solar Cells and Other Large Area Devices.” Conference on Advanced Thermal Processing of Semiconductors RTP, Idaho, 1996.

- Singh, R., R. Sharangpani, K. C. Cherukuri, Y. Chen, D. M. Dawson, K. F. Poole, A. Rohatgi, S. Narayanan, and R. P. S. Thakur. “How Rapid Isothermal Processing Can Be a Dominant Semiconductor Processing Technology in the 21st Century.” Material Research Society, San Francisco, CA, April 1996.

- Doshi, P., J. Mejia, K. Tate, S. Kamra, A. Rohatgi, S. Narayanan, and R. Singh. “High Efficiency Silicon Solar Cells by Low Cost Rapid-Thermal Processing Screen Printing and Plasma Enhanced Chemical Vapor Deposition.” IEEE Photovoltaic Specialists Conference, Washington D.C., May 1996.

- Rohatgi, A., P. Doshi, and S. Kamra. “Highest Efficiency RTP Silicon Solar Cells by Rapid Thermal Diffusion and Oxidation.” European Photovoltaic Solar Energy Conference and Exhibition, Barcelona (Catalunya), Spain, June 1997.

PROJECT HIGHLIGHTS
BP Solar International, Inc. (formerly Solarex, Inc.)

- Doshi, P., J. Moschner, J. Jeong, A. Rohatgi, R. Singh, and S. Narayanan. “Characterization and Application of Rapid Thermal Oxide surface Passivation for the Highest Efficiency RTP Silicon Solar Cells.” IEEE Photovoltaic Specialists Conference, Anaheim, California, September 1997.

- Rohatgi, A. and S. Narasimha. “Effective Passivation of the Low Resistivity Silicon Surface by a Rapid Thermal Oxide/PECVD Silicon Nitride Stack and its Application to Passivated Rear and Bifacial Si Solar Cells.” Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna, Austria, July 6-10, 1998.

- Rohatgi, A., P. Doshi, A. Ebong, S. Narasimha, T. Krygowski, and J. Moschner. “Rapid Processing of Low-Cost, High-Efficiency Silicon Solar Cells.” IUMRS-ICA International Conference in Asia, May 1999.

- Rohatgi, A. “Rapid Thermal Processing of High Performance Dielectrics and Silicon Solar Cells.” Symposium on Advances in Rapid Thermal Processing, Dielectrics Science and Technology Society Proceedings, Seattle, Washington, May 1999.

- Singh, R., A. Rohatgi, K. Rajan, S. Venkataraman, and K. F. Poole. “Rapid Thermal Processing as a Photovoltaic Manufacturing Technology for the 21st Century.” ECS Symposium, PV for the 21st Century, Seattle, Washington, May 3-6, 1999.

- Ebong, A., M. Hillali, and A. Rohatgi. “Rapid Photo-Assisted Forming Gas Anneal (FGA) for High Quality Screen-Printed Contacts for Silicon Solar Cells.” IEEE PVSC, Anchorage, Alaska, September 15-22, 2000.

- Ebong, A., Y. H. Cho, M. Hilali, A. Rohatgi, and D. Ruby. “Rapid Thermal Technologies for High Efficiency Silicon Solar Cells.” Photovoltaic Science and Engineering Conference, Cheju Island, Korea, June 11-15, 2001.

- Rohatgi, A., A. Ebong, V. Yelundur, and A. Ristow. “Rapid Thermal Processing of Next Generation Silicon Solar Cells Workshop on the Physics of Semiconductor Devices, New Delhi, India, December 14-18, 2001.

- Jeong, J. W., Y. H. Cho, A. Rohatgi, M. D. Rosenblum, B. R. Bathey, and J. P. Kalejs. “Rapid Thermal Processing for PECVD SiN-Induced Hydrogenation of High-Efficiency EFG Silicon Solar Cells.” IEEE Photovoltaics Specialists Conference, New Orleans, Louisiana, May 20-24, 2002.

- Bowden, S., D. S. Kim, C. Honsberg, and A. Rohatgi. “Rapid Thermal Processing for Front and Rear Contact Passivation.” IEEE Photovoltaic Specialists Conference, New Orleans, Louisiana, May 20-24, 2002.

- Rohatgi, A., V. Yelundur, J.W. Jeong, M. Hilali, and D.S. Kim. “Rapid Thermal Processing Enhanced Hydrogenation and Screen-Printed Contacts in Silicon Ribbon Solar Cells.” National Center for Photovoltaics and Solar Program Review, Denver, Colorado, March 24-26, 2003.

- Meemongkolkiat, V., M. Hilali, and A. Rohatgi. “Investigation of RTP and Belt Fired Screen Printed Al-BSF on Textured and Planar Back Surfaces of Silicon Solar Cells.” Conference on Photovoltaic Energy Conversion, Osaka, Japan, May 11-18, 2003.

- Rohatgi, A., V. Yelundur, J-W. Jeong, D. S. Kim, and A.M. Gabor. “Implementation of Rapid Thermal Processing to Achieve Greater than 15% Efficient Screen-Printed Ribbon Silicon Solar Cells.” Conference on Photovoltaic Energy Conversion, Osaka, Japan, May 11-18, 2003.

- Nakayashiki, K., D. S. Kim, A. Rohatgi, and B. R. Bathey. “Understanding of the RTP-assisted Reduction of Hydrogen Dissociation from Defects in EFG Si.” Photovoltaic Science and Engineering Conference, Bangkok, Thailand, January 26-30, 2004.

- Rohatgi, A., D. S. Kim, V. Yelundur, K. Nakayashiki, A. Upadhyaya, M. Hilali, and V. Meemongkolkiat. “Record-High-Efficiency Solar Cells on Multicrystalline Materials Through Understanding and Implementation of RTP-Enhanced SiNx-induced Defect Hydrogenation.” Photovoltaic Science and Engineering Conference, Bangkok, Thailand, January 26-30, 2004.